NATIONAL BUREAU OF STANDARDS

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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

NBS/RIA Robotics Research Workshop

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NBS/RIA Robotics Research Workshop

Proceedings of the NBS/RIA Workshop on Robotic Research,
Held at the National Bureau of Standards in
Gaithersburg, MD, on November 13-15, 1979

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ABSTRACT

The NBS/RIA Robotics Research Workshop had two objectives: 1) To provide a forum for structured discussions between researchers in robotics and manufacturers and users of robot systems; and 2) To develop a consensus forecast of future developments in sensors and control systems for industrial robots.

The Workshop brought together 31 researchers, manufacturers, and users of industrial robots in order to determine the needs and priorities for future research in sensors and control techniques for industrial robots. There were no formal papers; instead, small group discussions and presentations and the preparation of a Delphi Forecast were used to address research needs and priorities.

Key words: Delphi Forecast; robotic control; robot vision; robotic assembly; robotic standards; robotics research.

I. INTRODUCTION

On November 13-15, 1979, a Workshop on Robotics Research was held at the National Bureau of Standards in Gaithersburg, Maryland. The Workshop, which was arranged by the National Bureau of Standards in cooperation with the Robot Institute of America, had two objectives:

1. To provide a forum for structured discussions between researchers in robotics and manufacturers and users of robot systems; and

2. To develop a consensus forecast of future developments in sensors and control systems for industrial robots.

The Workshop brought together 31 researchers, manufacturers, and users of industrial robots in order to determine the needs and priorities for future research in sensors and control techniques for industrial robots. There were no formal papers; instead, small group discussions and presentations and the preparation of a Delphi Forecast were used to address research needs and priorities. The purpose of the report is to document the proceedings of this Workshop.

Attendees were split into 10 small groups: assembly, control systems, end effectors, welding, programming language, manufacturing systems, inspection, touch and force sensors, vision I, and vision II. There were two vision groups because of the intense interest in this area. The results of these small group discussions are presented in Part II of these Proceedings.

A Delphi Forecast on needs and priorities for sensor and computer control technologies was prepared by the participants. The first round was prepared prior to the Workshop and was discussed the first evening. The second round was prepared the morning of the second day, and discussed that same afternoon. A third round was then prepared and turned in at the end of the meeting. The results of the third round are presented in Part III of these Proceedings.

Key conclusions that can be drawn from the Delphi Forecast are:

1. Sensor-controlled movements of robots appear to be a highly desirable feature for present and future applications of robots. The most immediate economic benefit was simple vision in most application areas. The second most valuable sensory capability was different for different applications; proximity was

second for spot welding and arc welding; simple and complex force for drilling, routing, and grinding; complex vision and simple force for assembly; and touch for machine tool and press load/unloading.

2. Robot users felt that a cost of more than $10,000 could be justified for simple vision; less than $4,000 for proximity, simple force, and touch; and about $23,000 for complex vision.

3. There was a strong consensus among all participants that simple vision is the first priority for research and development efforts.

4. All sensory capabilities, including complex vision, should reach commercial availability before 1985 with at least 10 per cent of robots shipped that year having at least one of the listed sensory capabilities.

5. For all the applications addressed, the position and orientation of the majority of workpieces are known to within plus or minus one inch and plus or minus 20 degrees. In most cases, this is within the capabilities of simple vision systems.

6. Line following would be highly useful only for spot welding. However, robot mobility (the robot mounted on a platform which can be moved about allowing the robot to operate in many locations) would be useful in over 20 per cent of all applications. The exception was small parts assembly.

7. A shift was seen during the 1980's from the point-to-point control systems to systems with coordinate transformation, off-line programming, and trajectory optimization.

8. By 1990 25 per cent of all robots shipped will be incorporated into computer-aided manufacturing systems.

9. The market for industrial robots in 1985 is estimated to be approximately $225 million, and $780 million in 1990. This represents a projected growth rate of about 30 per cent per year.

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II. DISCUSSION GROUPS

Each participant was assigned to two groups on the basis of his or her expressed interest. Five groups met the morning of the second day, and five met the morning of the third day. These groups directed their efforts toward identifying and quantifying as much as possible the principal research issues related to their particular group topic. After these individual meetings, all of the participants were brought together. A spokesperson for each group presented a summary of the consensus view of the group's discussions. This allowed all of the participants to review and contribute to the central points identified in the smaller groups.

The chairperson of each group, assisted by a scribe, prepared a written summary which is reprinted here.

1. ASSEMBLY

Group Members:

Ward McClure - Chairperson, Texas Instruments
Joseph Gibbons - General Electric
Mitchel Ward - General Motors
Floyd Holroyd - General Motors
Peter Rogers - Unimation
Phil Villers - ComputerVision
Robert Stauffer - Robotics Today
Peter Will - International Business Machines
Gordon VanderBrug - National Bureau of Standards

A. Introduction

The application of robots to the assembly of products continues to be exceedingly difficult; however, some progress is being made. Assembly is recognized as being one of the last frontiers for automation of small-lot, batch manufacturing operations. At present, product assembly is primarily a manual task. In order to be successful in this area, any machine or set of machines will be required to perform jobs which are generally today designed for people. These jobs utilize the persons' abilities of sensing, implicit inspection, dexterity, common sense, reasoning, and relatively easy trainability.

B. Group Report

The following is a summary of the issues discussed and conclusions reached by the assembly group:

There are two basic assembly categories. They are:

- Loose assemblies (loose tolerance and unfastened);

- Close tolerance (peg-in-the-hole type assemblies).

The majority of assembly applications in industry are loose with tolerances typically greater than .005 inches.

Work is required in the identification and evaluation of alternative system configurations of feeders, robots, material handlers, etc., with respect to an optimization criterion (usually cost per part).

Academic and applied work is needed on:

- The design of parts for assembly.

- The design of products for assembly.

- Robot-compatible parts presentation.

- Parts inspection in the broadest sense.

It was felt that the primary robot technology required consisted of machines with effective cycles of 2 to 6 seconds and .25 mm (.010 inches) accuracy. This speed and accuracy is available commerically today (1979).

Economic justification is still based upon a 1-2 year payback criteria because versatility across basic applications boundaries has not yet been demonstrated.

A theory of error recovery needs to be developed, e.g., an error is recoverable if it can be detected before it can be no longer disassembled.

Contact sensors slow humans and machines: The use of non-contact sensors is recommended where possible.

Disagreement still exists concerning the desirable number of degrees of freedom needed for product assembly. The consensus was that for most products 4 degrees are sufficient; however present robots need 5 degrees to provide a correct implementation.

Limp parts such as wire and cables have not received enough attention.

A special grade of parts (close tolerances and 100 per cent fit-for- intended-use) would be desirable to minimize line downtime due to defects entering the system.

Very fast inspection devices are required so that a 100 per cent inspection policy can be specified in lieu of or in addition to the automation grade of parts.

Insufficient attention has been paid to the problem of training users to program, operate, and maintain robots.

Fasteners cause problems in practice due to feeding, quality, and variety.

Simple vision integrated with a parts conveyor has much to offer in parts feeding.

Assembly, while still not widely developed, is much brighter in outlook than was concluded in the 1977 Delphi. Substantive application issues are being explored and the detailed deficiencies of existing tools, feeders, and other auxiliary equipment are being exposed as the area gains maturity and is approaching practical development.

2. CONTROL SYSTEMS ARCHITECTURE AND IMPLEMENTATION

Group Members:

Domenic Zambuto - Chairperson, GTE Laboratories
Tony Barbera - National Bureau of Standards
Jerry Ennis - McDonnell Douglas
Riley Kuehn - Boeing
Richard Handwerg - General Dynamics

A. Introduction

It is very difficult to define or agree upon what would be the most appropriate control system architecture for integrated robot systems. This problem has been studied by the academic community, research institutions, and a number of industrial research laboratories. Each has developed their own architecture and programming languages.

A number of users of industrial robots in this country are upgrading the robot control system to interface with sensors, special devices (jigs, fixtures, etc.), data base systems, and other environmental conditions within their plants. This is done, in some cases, at the expense of not using the control system provided by the robot manufacturers because it did not produce the user-desired capability, or because the source code was not available from the robot suppliers.

The unanimous conclusion of the group, was that there is a need to develop a "Standard Interface" for industrial robots.

B. Group Report

The control group discussions focused on those attributes needed to improve the capabilities of today's industrial robots so that they can function in less structured environments.

Today's industrial robots function in constrained environments, performing their tasks by moving through pre-recorded sets of spatial points in a sequential manner. These programmed points are taught by leading the robot through the desired task and recording the joint positions along the way. In many applications, particularly those which require frequent changes, such as batch manufacturing, this type of activity can be very time-consuming and undesirable. However, with the coming of the low-cost microcomputer technology, more powerful robot control systems may be configured. Thus, research is needed to define and develop the robot

control system architecture in which processes can be carried out in parallel, in real time, and be sensory interactive within the robot's environment.

With this in mind, the group discussed and created a list of some of the desirable attributes of an advanced control system.

These were:

1. The control system should be modular and easily expandable. There should be clean interfaces between modules.

2. There should be easy communications between modules within the control system as well as with other sensors and devices operating within the environment of the robot.

3. The control system should interface with other data base systems so that robot programs can access part dimensions.

4. The control system should be easily maintainable through the use of self-diagnostics and self-calibration. In advanced systems it might even interface with manufacturing maintenance centers to dispatch maintenance personnel.

5. There should be a user-oriented high-level programming language which allows the programming of the robot through simple English-like command language. This language should be extensible; that is, it should allow for changes in input commands, control algorithms, sensors, and special devices. It should be possible to make additions and deletions with a minimum effort.

6. It should have off-line programming capability. This will be required to develop the robot's mainline (task) program without tying up the robot hardware system. This capability will aid in the integration of the robot into total computer-aided manufacturing systems. It is recognized that today's robots are nonlinear, and in off-line programming, this nonlinearity becomes a problem. A suggested solution is that each robot have a positioning calibration file that accounts for the non-linearity.

7. The control system and programming language should be independent of the robot

configuration, enabling its use with any robot. This notion of a general purpose control system and language should improve the portability of the control systems.

8. The control system should provide trajectory optimization. The group touched on this briefly by discussing the ongoing work at Purdue University. It was felt that adaptive optimization schemes needed for coordinated motion of robot joints based on a predefined path between two points will be extremely useful for future robot systems.

9. There should be obstacle avoidance and coordination control between multiple robot or other equipment.

10. There should be a floating zero reference so that a programmed robot task at a defined reference could easily be translated to perform the same task starting at a different reference.

11. There should be the capability to switch the servo-control function (under computer control) from a positioning servo to a force-torque servo.

12. It was felt that there exists a need to establish a "standard interface" for industrial robots. Figure 1 shows an interface between a possible real time control system and the robot.

Many issues were raised during the group discussion on the possibility of a standard interface. For example, one such question addressed how position commands from the real time controller would interface with the robot. Another such question was where the coordinate transformation function would be located. Many other issues were raised and the only conclusion formed was that it is a difficult problem to define and that possibly NBS-RIA might, together with the National Science Foundation, Electronic Industries Association, and the American National Standards Institute, initiate action on defining and establishing a "standard interface."

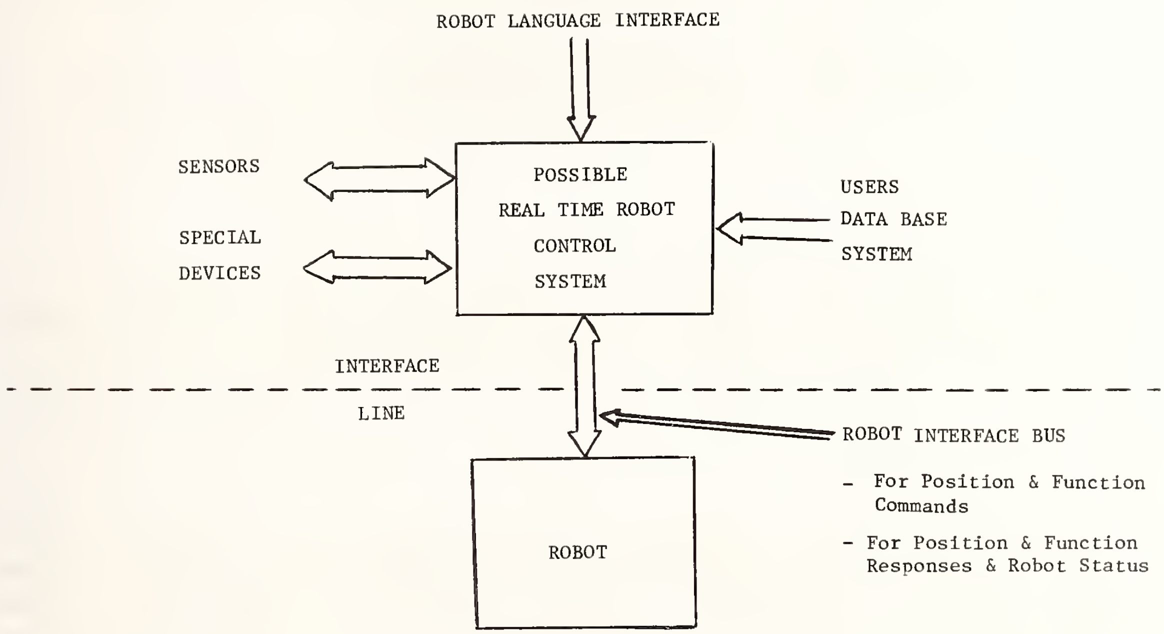

FIGURE 1

POSSIBLE ROBOT SYSTEM INTERFACE

3. ROBOT END EFFECTORS

Group Members:

Dan Evert - Chairperson, Aluminum Co. of America
John Birk - University of Rhode Island
Jim Lockett - Northrop Corporation
C. D. Mathes - General Dynamics
Ron Potter - Robotics Technology Inc.
Victor Scheinman - Stanford University

A. Introduction

For discussion purposes, the subject of end effectors was divided into two general application areas. For the most part, the needs in the two areas are different. The two application areas were: (1) part handling and (2) tool handling.

B. Group Report

The expressed need common to both categories of end effectors was standardization of an interface adapter with quick-change capability. It was recognized that more than one size of standard adapter would be required to accommodate the wide range of robot sizes. In part handling applications, the quick-change adapter will facilitate the handling of a wide variety of part geometries where several gripper configurations are used and must be interchanged frequently. In applications where the robot arm is being used to quick-change tools for drilling, tapping, and milling, a quick-change tool adapter would enable one robot to perform a variety of machining operations with minimum time required for tool change.

The standardized features of an interface adapter should include the following:

1. Mechanical connection providing a common mounting and securing system for all types of end effectors.

2. Electrical connection to provide an interface for electrical power and electronic signals to the end effector and electronic signals from end-effector-mounted sensors.

3. Hydraulic connections to the end effector for hydraulically powered actuators.

4. Pneumatic connections for pneumatically powered actuators.

All of the above interface connections should be the type of automatic connections which permit automatic tool changing when called for by the robot's control program.

The discussion of research and equipment development needs in the area of part handling end effectors centered around the idea of universal applicability. The assertion was made that there are few shapes which cannot be grasped by simple parallel jaw grippers. Hand pliers or tongs were offered as evidence supporting that statement. It was concluded that research work should be directed toward developing sensory systems to provide the intelligence needed for a robot to utilize this simple gripping mechanism effectively.

Special needs in the area of tooling type end effectors were discussed. It was pointed out that many of the tools used by robots for operations such as drilling, routing, milling, and grinding are designed around the adaptation of available hand tools. As such, these adaptations result in unsatisfactory performance, causing excessive deflection and chatter in many machining applications. To remedy this, a line of tools should be developed specifically for use by robots. These tools should be lightweight, compact, and rigid.

Additional work in the area of sensory feedback in machining applications is needed. Edge tracking and force sensing capabilities were cited as examples.

The subject of end effector dexterity was discussed briefly. Part reorientation in the hand to minimize robotic transfer cycle time requires a far more dextrous gripper than is currently available. End effector dexterity was also seen as a way to improve the overall robot/gripper system accuracy and repeatability. Fine movement of the end effector could "zero in" on positioning requirements outside the capabilities of the robot's hardware alone.

4. WELDING

Group Members:

Norman Maxey - Chairperson, Deere & Company
Dan Reinhart - Caterpillar Tractor
Dan Fitzpatrick - Prab-Versatran
Dick Hohn - Cincinnati Milacron
Brian Ford - ASEA

A. Introduction

The welding discussion covered both resistance welding, spot welding, and gas-metal arc welding. Due to constraints on time, arc welding was discussed in greater detail than resistance welding.

Arc welding is a process which joins two or more pieces of metal through fusion. Metal Inert Gas (MIG) welding was the arc welding process on which the group concentrated, largely because this was the process in which the participants had the most knowledge and experience.

Problems associated with arc welding are largely due to inconsistant joint fitup. Joint location and gap vary from part to part due to inconsistent cutting and forming operations. A human welder will vary welding parameters and the welding method to adjust for these variations. Today's robots will not automatically adapt to part variations.

Spot welding is a process used for joining two or more pieces of sheet metal together with resistance heat. Spot welding of automobile bodies is a typical use of this form of welding. Robots are used to carry spot welding guns to the workpiece. The workpiece is usually fixtured and in a known position in relation to the robot.

B. Group Report

MIG welding was the first process discussed. Deere and Caterpillar generally agree that the following are their reasons for reviewing robotic welding:

1. Integrity and/or quality of welds.

2. Productivity and environmental problems.

3. Weld appearance.

Joint location and gap variations are the biggest problems associated with robotic MIG welding. The joint location and gap problems are different for various metal thicknesses.

This group, therefore, broke the discussion into two categories - 1/4" and thinner sheet metal and thicker than 1/4" plate steel.

Following is a list of problems and conclusions the group felt were associated with the 1/4" and thinner sheet metal:

1. Joint location is the most significant problem associated with lighter sheet metal parts.

2. A non-contacting sensor is needed.

3. Vertical torch adjustment is less critical to the process than traversing adjustments.

4. The small weld size used with this gauge metal makes high robot accuracy and repeatability essential.

5. Sensor feedback adjustment should control 2 or more degrees of freedom.

6. Vision is the most desirable sensor control for robotic welding.

7. Sensors should be placed just ahead of the welding arc.

The problems and conclusions associated with the heavier than 1/4" plate steel are the same as above, with the following additions:

1. Sensory control for 2 or more degrees of freedom plus compensation control for gap variation is required. This automatic compensation should include wire feed change, voltage adjustment, arm travel speed, weave capability, etc. The welding parameters should be changed automatically as conditions change.

2. Robot accuracy and repeatability are important, but not as critical as for the sheet metal welding. The heavier welds allow for greater tolerances in point of arc placement.

The manufacturers stated that the sensor need, to some extent, is being addressed now. Each welding robot manufacturer is approaching the problem in a manner which they feel will satisfy the users' need.

However, it was felt that the present effort is not on a large enough scale and additional effort should be started

in the area of sensor-controlled arc welding. The research should be at least on the scale that assembly is being investigated today. Welding is an environmentally undesirable production process which is essential to American industry. More than 65 million worker hours and 540 million pounds of wire are expended on MIG and Tungsten Inert Gas (TIG) welding each year in the United States. Adaptive control through the use of sensors would allow for wide usage of robots for welding by American industry. There is a large potential productivity gain to be acheived in this area.

The group only knew of one research institution with an ongoing research project using sensors for welding robots. Stanford Research Institute (SRI) is attempting to develop vision for welding robot control.

Spot welding as it is commercially available today is widely accepted by American industry. Sensors could be utilized if they were developed, but they are not as essential for spot welding as for gas-metal arc welding. If sensors were to be developed, proximity sensors and vision would be the most valuable.

C. Additional Discussion

Mobility in a robot would satisfy a limited need. Some need exists for a robot which would weld from more than one station on a single large fixture. More benefit would be realized if a robot could move from one location to another, which would allow for welding on more than one fixture. A robot used in these applications should be non-servo controlled for movement between locations.

Sensors should be small enough to allow access to small confined areas.

Parts must be designed to allow for automation. Manufacturing tolerances on simple parts must also be controlled so that subsequent welding processes can remain largely unchanged from part to part.

Research associated with automatic process control must be conducted. When the sensor indicates that a change has occurred in the part joint, the control must know what welding parameter to modify (wire feed, voltage, weave, robot arm speed, call operator, multiple pass, etc.) The logic associated with these changes must be established.

5. PROGRAMMING LANGUAGES

Group Members:

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Richard Handwerg - General Dynamics
Dick Hohn - Cincinnati Milacron
Dan Reinhart - Caterpillar Tractor

A. Introduction

Language is the means by which a user communicates to the robot system the actions to be performed. Historically, a robot has been "taught" a path. Using a "teaching pendant" the robot was moved through the desired path and the required setpoints were recorded for future playback. With the increasing sophistication of robots and their applications, this teaching method has evolved to a more complex procedure of first laying out a nominal path, then using both a teaching pendant and a keyboard-type device for entering the path logic, functional description, and setpoints.

This group directed their discussion toward the environment of the robot programmer and to general areas of future development within robot languages. Specific languages or language constructs were not addressed.

B. Group Report

The first topic addressed was to clarify some of the terminology. There was general agreement that with today's robots, "programming" and "robot program" are technically more accurate terms than "teaching" and "robot path" respectively, although the terms are generally used interchangeably.

Programming is a) establishing the logic and functional description of a program and b) specifying the required data. The combination of logic and data is a program. The required data may be established by teaching, as is widely done today, or may be provided by an external source such as a sensor or a data base.

The second issue was the question of who does the programming. There was general agreement that in the future robot programming will be done by people comparable to today's NC (Numerical Control) programmers. In certain application areas such as welding, these programmers would first need to be experts in the process being performed by the robot and

secondly computer programmers. However, there is a definite need for the operator on the production floor to be able to "touch up" a program.

The final topic discussed was that of what general areas of language development should be addressed by researchers and manufacturers today. The following areas were discussed:

1. Off-line programming is the process of creating all or part of a robot program without using the robot directly (using a spare robot for program development is not off-line programming as defined here). As the logic development phase of robot programming continues to grow, more of the techniques of computer programming are needed to support the development of robot programs. Keyboard entry and editing of programs and data, program listings, and simulated execution of programs are examples of features which should be generally available.

2. Integration of sensor capability into robot languages is an important consideration. A general theme of this workshop was the importance of sensors in robot applications. Wide usage of sensor-based robot systems requires the integration of constructs into the robot language for using these sensors.

3. The need to access geometric data bases is becoming more desirable. As more industries maintain computer data bases which describe the geometry of parts and assemblies, the need for an interface between the robot language and these data bases grows. These data bases can be used almost directly to provide data such as hole locations, or they can be used indirectly to provide data to support high-level assembly tasks.

4. Support for creating and maintaining program data bases is a growing need. This computerized data base would be a replacement for the cassette tapes of today. This central data base would require the ability to download line programs from the data base to the robot as well as to upload programs from the robot into the data base. This general support would eliminate the need for special devices at the robot station for program loading and would greatly simplify the operator interface for program loading, touchup and backup. Automatic program loading

based on part identification or sensor input would be possible.

This group did not consider the above to be a complete list, but rather, these were the topics discussed during the time available.

C. Additional Discussion

Following the group report to the full workshop, several other issues were raised.

There is a need for some standardization of robot terms. NBS responded that they are planning to produce a set of definitions next year.

The question arose as to whether there should be a family of languages for robots where each language is tailored to a class of applications. At the other extreme was the question of a general manufacturing language for programming a complete application. The robot language would be a subset of this general language.

The question was raised as to whether a level of language standardization comparable to the APT CLTAPE files should be developed. There was general agreement that this was desirable and that at least the research community should begin pursuing this question.

6. MANUFACTURING SYSTEMS

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Dan Fitzpatrick - Prab-Versatran
Norman Maxey - Deere & Company
Ron Potter - Robotics Technology Inc.

Others in attendance:

Lori Mei - Society of Manufacturing Engineers
Brad Smith - National Bureau of Standards
Robert Stauffer - Robotics Today
Gordon VanderBrug - National Bureau of Standards

A. Introduction

The session was opened with an attempt to define a manufacturing system. After some discussion, the consensus was that a manufacturing system might be defined as: "Men, materials, machines, and processes combined to make a product." In the context of the workshop, it was decided that "robots" should be substituted for "men" in this definition.

B. Group Report

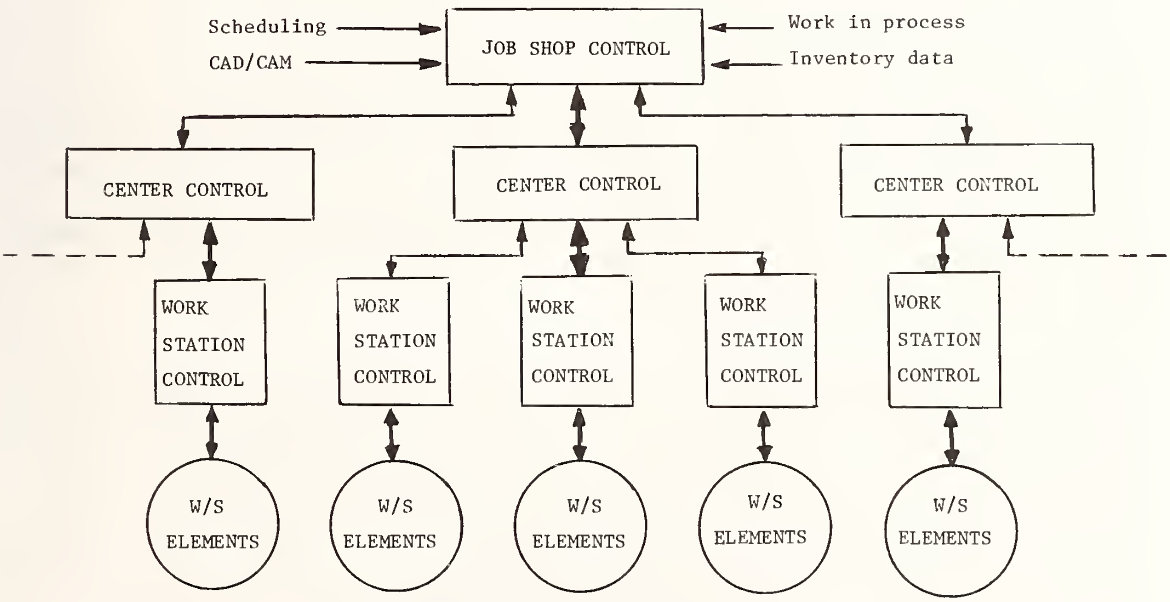
It was felt by most of the group that manufacturing systems could be classified as "simple" or "complex." From this point, the elements of a simple manufacturing system were identified. These were:

Machines
Controls
Material movers
Robots
Interlocks

In a simple or "stand-alone" manufacturing system, the level of integration of these elements is very basic. Often there is no central control; each element of the system contains its own control capability. An overall management function is still necessary, however, and this is usually vested in the robot. Through simple interlocks, such as hard wired links between controllers, the robot initiates the actions of the other elements of the system at appropriate times. Execution and termination of these actions are handled by each element's own control, which then returns signals to the robot.

It was felt that current state-of-the-art technology is sufficient to support simple manufacturing systems. In fact, many examples of such systems exist today, from die cast-quench-trim and multiple machine tool loading-unloading to multiple station tooling/conveyor/robot systems for automobile spot welding.

The discussion then turned to complex or integrated manufacturing systems. Complex systems contained the same basic elements as simple systems, plus interfacing, monitoring, and supervisory control. A complex manufacturing system might, in fact, be made up of a linked group of simple manufacturing systems, operating as manufacturing cells. A control hierarchy is involved, with several functional levels, as diagrammed below:



Simply described, this hierarchy functions as follows: Each Work Station (WS) in this diagram corresponds to a simple manufacturing system, with one exception; the existence of an overall or supervisory control, the Work Station Control (WSC). The individual WS's are linked, through their WSC's to the Center Control (CC). The CC monitors each WSC and schedules the materials and operations for each WS, based upon input from the Job Shop Control (JSC). The CC also transmits data regarding production, WS availability, etc., to the JSC. The JSC is responsible for supervising, coordinating, and monitoring all operations in the shop through several CC's. The JSC is also responsible for production

planning and scheduling and for development of management information. Thus, there are inputs to the Job Shop Control from sources other than the shop floor. CAD (Computer-Aided Design), CAM (Computer-Aided Manufacturing), MIS (Management Information Systems), and group technology may all contribute information to the Job Shop Control.

It was determined that few, if any, complex or integrated manufacturing systems exist today to the level described. Several factors inhibiting growth of manufacturing systems to this level were presented: economics, lack of documented experience, lack of systems development sources, and lack of systems vendors. Interestingly, technology was not cited as a major inhibiting factor.

The discussion was then directed to the technology and hardware needed to facilitate complex manufacturing systems. Having determined that technology and hardware were not holding back the development, the purpose was to determine what, if any, technology might encourage complex manufacturing system development. One factor which might apply was the enhancement of robot capabilities through development of vision systems, control systems, end effectors, sensors other than vision, programming, and control languages. In short, all of the items under discussion in other small group sessions would be integrated into manufacturing systems, both simple and complex.

Another robotic need identified was the need for increased interface capabilities, particularly with host computers. High-speed data interfacing, ability to download entire programs, ability to download while in program execution, standardized interface ports and data structures, multiplexed inputs and outputs were felt to be areas of deficiency in present robot control systems. It was felt that development of these capabilities should be accomplished by the robot vendors. Little basic research was necessary in this area.

Basic research, according to the group, should be concentrated on the architecture of complex manufacturing systems. One significant need is for a "cookbook" or "handbook" to guide users in the planning and development of complex manufacturing systems. Universality of programming language and data base structure were considered to be extremely important. Another basic research area should be the development of monitoring systems, including sensors and software capable of not only detecting problems and initiating shutdown, corrective or alternative action, but also capable of predicting breakdowns and initiating preventive actions before they occur. Another need is for group technology methods which are applicable to small-batch manufacturing.

In summary, the group felt that the current state-of-the-art is adequate to permit continued implementation of simple or stand-alone manufacturing systems. However, development of complex or integrated manufacturing systems will not proceed at a rapid pace in the near future, due to economics, lack of experience, and lack of knowledge in the structuring and implementation of such systems.

7. INSPECTION SYSTEMS

Group Members:

Roger Nagel - Chairperson, National Bureau of Standards
Nelson Corby - General Electric
Brian Ford - ASEA
Floyd Holroyd - General Motors
Riley Kuehn - Boeing
Ward McClure - Texas Instruments
Peter Will - International Business Machines
Russ Young - National Bureau of Standards
Dominic Zambuto - GTE Laboratories

A. Introduction

The inspection area was found to have five separate subtopics with increasing complexity based on inspection data. They are, in order: dimensional tolerances, surface quality, part integrity (which was considered to be a catchall), material quality, and functional test. For discussion purposes, explicit and implicit inspection were defined as follows:

> Explicit inspection is the performance of a required inspection task.
>
> Implicit inspection is a manufacturing check which is performed, or should be performed, as part of some manipulation task.

There is a fundamental problem because common-sense manufacturing checks are not documented as part of the processes which are performed in manufacturing. This is compounded by the fact that people cannot describe algorithmically the process they go through in discovering errors and in doing the implicit inspections as part of their tasks.

B. Group Report

The inspection group discussions centered on several topic areas. The first of these were robotic considerations. We need to know the effect of the weight of a sensor on the accuracy of a robot. We also need to know how an inspection system can get accurate data independent of the robot. It was pointed out that there is a need for a family of inspection robots to be designed and developed for that purpose. In particular, it was suggested that the first such robot have a 5- to 10- pound part capacity and that it be the size of a bread box.

Research topics identified during the discussions were the

following:

Fast complex vision

A micrometer or other measuring device in the hand or the fingers of the robot

High precision, non-contact three-dimensional sensors.

Testing and inspection of printed circuit boards.

A high-speed arm which moves to a high-precision end point which is determined externally.

Determining the completeness of parts, their orientation, location, the components present, etc.

Measuring and determining the gradation of surface finishes during an in-line process.

The following tasks were determined to be currently possible with additional compute power as made available by microprocessors.

Combinations of simple sensor measurements; for example, the measurements being performed on car bodies by Ford and Volkswagen.

Simple vision tasks such as counting holes that go through or blind holes. Locating edges and corners.

Determining the presence or absence of features such as labels or other markings on the parts.

In general, it was felt that the problems which can be solved at this point are those that require simple sensors, and will be done by making a large number of measurements by utilizing the compute power offered by todays microprocessors. What is needed in the future are designs for inspection of parts, assemblies, robots, and sensors. It is felt that inspection will be truly automated when each of these items has been designed with inspection tasks in mind. A major impediment to progress in inspection was considered to be the lack of fundamental knowledge. It was recommended that an industrial engineering group survey the manufacturing process for a sample application. With respect to the chosen application, they should consider a list of steps involved in that manufacturing process, itemize what can go wrong, determine what class of sensors would be needed, and what automatic tasks can be performed. When this knowledge base has been collected, it would be important to analyze it for commonalities, to group the tasks in families, and to

order them by complexity. It was suggested that the NBS would respond favorably to a request to perform this by the Society of Manufacturing Engineers or other responsible group.

It was further postulated in a group discussion that approximately 20 per cent of the total manufactured output is either not inspected or poor algorithms are used. There is room for improvement of products, avoidance of value-added steps, and a general increase in productivity by proper inspection techniques.

The group felt that future directions for inspection would be toward in-process inspection, 100 per cent inspection, and designs for inspection. We need quality functional parts. We must avoid human inspection because of human fraility, boredom, and the inappropriateness of the task for human beings.

Driving forces that will move us in the directions mentioned above are the need for improved quality and productivity, government regulations, and the economics of discovering after value-added steps that the product had a flaw at the beginning. It was pointed out that the high cost of recall programs experienced by automobile companies and others has helped focus the need for in-process inspection and 100 per cent inspection.

In summary, the group reached the following conclusions:

> We need a robot family designed for inspection.
>
> We need to conduct a manufacturing survey of the tasks and problems involved in inspection.
>
> We must move toward automatic inspection, in-process inspection, and 100 per cent inspection.
>
> There is a need to educate the practitioners about the current state-of- the-art, so that they can use it now and help it evolve to meet future needs.

8. TOUCH AND FORCE

Group Members:

Victor Scheinman - Chairperson, Stanford University
Joseph Gibbons - General Electric
C. D. Mathes - General Dynamics
James Albus - National Bureau of Standards

A. Introduction

The group discussions focused on definitions, directions, and problems rather than specific applications or implementations. From an industry point of view, force or touch sensing presently means the equivalent of LVDT's and springs or microswitches on the gripper tips. This is force and touch sensing of the simplest form. Obviously, further development will occur. We felt that good definitions of force and touch sensor categories are a must for further discussion.

B. Group Report

Touch sensors would include both single and multiple binary (contact) or proportional omni-dimensional force and/or displacement sensors intended for gripper or tool surface mounting or placement where contact information is desired.

Force sensors would include simple devices to measure one-dimensional force information while complex sensors would include devices capable of measuring forces, moments, or torques in multiple dimensions (up to 6 dimensions). Generally, these force sensors would be considered to be physically located away from the actual contacting end effector surfaces, such as at the base of the fingers, between the end effector and manipulator, at a joint, or in the robot base. They could even be devices such as joint torque controllers relying on pressure or current measurement in the actuators. We recognized the need for force, moment, and torque information but found it difficult to describe applications in terms of force sensing to get the end results we want.

Specific recommendations of the group include development of a "touch camera", and a gripper mounted unit which can map the surface features of touched objects. Applications such as the proverbial bin-picking problem abound, with a possible need greater than that of vision.

Further hardware and software developments are necessary, especially in the area of increasing the resolution (larger array sizes, shapes, and increased density), simplifying the

wiring, and ruggedizing the contacting sensor surfaces. It is also necessary to properly and efficiently correlate localized and partial feature sensing with computer models of whole objects.

Force sensor development should proceed with improved six-axis sensors having greater dynamic sense range, greater uniformity of axis sensitivity, and fully effective overload protection. Array processors should be introduced to rapidly resolve the force and moment components. New algorithms must be developed and implemented in software to effectively interpret and employ the force information derived from these sensors.

The subject of compliance was brought up during the workshop discussion. In many prototype contouring tasks such as routing or grinding, passive compliance through low spring rate flexure or spring-mounted tools has been effectively used to implement simple force control or servoing. For fast point to point transfer motions, compliantly mounted end effectors must be locked in place to reduce oscillations. With respect to the remote center compliance device (RCC), a passive mechanical device which allows for accommodation or positioning error when mating close-fitting parts (bearing insertion, dowel pin in hole, etc.), the whole group discussion concluded that it is not a sensor, but a tool or accessory because it is not an active device, nor is there any active process directly associated with operation of the device.

An alternative is active force servoing with compliance developed through the sensor-computer-manipulator loop, in which a structurally rigid manipulator is rapidly servoed on force information generated by an active force sensor. Although demonstrated in the laboratory, this approach has not yet been implemented in industrial tasks. The discussion group felt that more work on force control of robots was necessary, and that the subject of active vs. passive compliance or combinations required more study.

Early in the workshop section of the discussion, someone made a comment that it seemed hard to believe that about 5 per cent of a proposed ideal research budget could be spent on force and touch when microswitches work well. As a result of the discussions, the Delphi forecast number was increased to about 11 per cent. The key to further development and applications in the area of force and touch sensing and control is describing problems and tasks in terms which encourage the use of these sensor-based systems as alternatives to high precision tooling, ordered part presentation, and defect-free tight tolerance components.

9. VISION I WORKSHOP

Group Members:

James Albus - Chairperson, National Bureau of Standards
Richard Becker - Chesebrough-Ponds
Nelson Corby - General Electric
William Tanner - Tanner Associates
Roger Nagel - National Bureau of Standards

A. Introduction

This workshop centered its discussion on the outstanding problems in robot vision. This question was broken down into four problem areas:

- Types of Applications
- Training the Vision System
- Vision System Capabilities
- Interfaces between the Robot and the Vision System

B. Group Report

Types of applications

It was decided that the two most important applications of robot vision were: a) determination of part position and orientation, and b) inspection. In most cases, there is no need to recognize what a part is. That is almost always known. The real problems are: where is the part, what is its orientation, and is it free from defects?

Giving a robot the ability to determine the position and orientation of parts will greatly expand the number of robot applications. There are relatively few applications where parts can be presented to a robot with sufficient precision that the robot can blindly grasp them with no adjustment in the pickup point. Parts feeders that present parts in precise position and orientation are expensive and often unreliable. Pallets or conveyors that can preserve part orientation throughout the manufacturing process are not practical in a large number of cases. It may be possible to improve this situation somewhat in the future, but there will always remain a large number of applications where there are significant unknowns in position and orientation. It seems likely that vision will be the most practical and reliable means for the robot to acquire this information.

In many cases it is relatively simple to feed parts so that they do not overlap or touch. When this is done, the vision problem is vastly simplified. Often a simple silhouette

binary image is adequate. Simple measurements on such an image (like area, first and second moments, perimeter, and major and minor axes) are all that is needed for robot part acquisition.

Nevertheless, at least two laboratories (Rhode Island University and NBS) are actively working on vision systems that can deal with touching and overlapping parts. The strategy in both places is to split the problem into two parts, using one set of vision algorithms to find and isolate a single part, and another set of vision algorithms to determine its position and orientation.

Inspection is the second major application area of robot vision systems. Inspection is implicitly performed by human workers every time a part is manipulated. Robot vision will allow the robot to perform the same type of simple checks for part integrity. Explicit inspection, of course, is itself a major area of application for machine vision whether or not it is coupled with a robot. Human inspection, while capable of much greater sophistication, is subject to error due to fatigue, boredom, and distraction. The types of inspection discussed were: verification of the number of parts, verification of part type, verification of correct labeling, and verification of the existence of holes, threads, flanges, etc. It was felt that many of these types of inspection tasks can be performed by robot vision systems in the near future. More difficult jobs, such as measurement of dimensional tolerances, inspection of surface finish, and detection of cracks, chips, and scratches, are still research topics.

Training the Vision System

From a user standpoint, the methods available for training the vision system to perform a task are critically important. The simplest method for the user is a "train by showing" technique. This implies that the vision system has some internal method of selecting what features are important. Most vision systems currently available require a significant degree of user knowledge concerning the internal workings of the processing algorithms. Many customers are misled by vision "systems" which aren't really systems at all. They are only hardware that customers must make work. Most users do not have the expertise to turn this equipment into reliable working systems.

In most installations there is a great deal of cut and try required in adjusting lights, selecting appropriate features, etc. Often, satisfactory operation of the vision system is subject to parameters which may drift with variations in lighting. In order for robot vision to have wide

usage, a great deal of effort needs to go into design for robustness and the development of turn-key systems which require very little user sophistication.

It was agreed that current vision systems are at a level of technological development comparable to robots 15 years ago. What is needed is for manufacturers to offer totally engineered systems like many robot manufacturers offer today. It was felt that there is great opportunity for "vision system houses" to do robot vision systems engineering and to market turn-key vision systems incorporating simplified user interfaces and vision programming languages.

Vision System Capabilities

There was a great deal of discussion of the relative merits of binary versus grey scale vision. Richard Becker noted that Chesebrough-Ponds used only grey scale in its inspection applications. Nelson Corby replied that General Electric used binary images in most of their work. It was mentioned that General Motors has expressed to SRI the opinion that there should be no more effort spent on binary images, and that all future systems work with grey scale images. James Albus suggested that there is a middle ground where the images to be processed are binary, but that the threshold for slicing the image can be adjusted in a sophisticated way to discriminate the critical image features. Thresholds can themselves be images which may either be derived from the camera or generated by the computer by algorithmic processes. Roger Nagel pointed out that various techniques of projecting structured light and analyzing the effects of part translation or rotation can generate important visual information. Often binary images resulting from these techniques contain more information relevant to manipulation than can be obtained from much more complicated analyses of grey scale images taken from a single viewpoint.

Interfaces Between the Robot and the Vision System

Clearly, if the robot is to use information obtained from a vision system, there must exist an interface between the vision system and the robot control system. There are three types of information which the robot needs to be able to accept:

a) Branch on external condition. In this case, the vision system merely detects the presence of some condition which causes the robot program to alter its behavior by executing a branch. This is the simplest type of interface and is presently available on almost all robots.

b) Go to a position and orientation defined by external data. In this case, the vision system may compute the position and orientation of a part and provide the robot with this information. This requires that the robot control system be able to substitute external data in place of data already stored in its program. Most manufacturers have some capability along these lines, although the substitution process is often a very awkward procedure. Many robot control systems do not separate data from programs, and many others do not have any simple methods of substituting external for internal data points.

c) Execute an incremental move based on external data. In this case the vision system may compute the relative distance between the gripper and the part to be acquired. This type of move is required for visual servoing. We are not aware of any robot that currently has the capability for incremental moves in both translation and rotation, although incremental translational moves are possible on some models.

There is also a need for communication from the robot to the vision system. The types of information that flow in this pathway are commands to the vision system to take pictures; parameters for lighting, thresholds, etc; instructions as to what picture processing algorithms to employ; and even predictions or expected data based on what position the robot is in or what phase of the task execution is operative. The robot control system may also ask questions of the vision system.

The issue of data formats and protocols for this robot-vision system interface was raised but not discussed in any depth. This is a large and important topic which will require much further study.

10. VISION II

Group Members:

John Birk - Chairperson, University of Rhode Island
Dan Evert - Aluminum Co. of America
Jim Lockett - Northrop Corporation
Peter Rogers - Unimation
Phil Villers - ComputerVision

A. Introduction

The following assertions were supported by the group:

1. There is no fundamental reason why there shouldn't be more commercially available equipment for vision.

2. In-house industrial activities in production demonstrate the technical feasibility of using vision. More information is needed to judge economic feasibility.

3. Three sources might develop vision: companies who consider it a profitable business, robot suppliers who can expand the range of application, and robot users who want to save money.

4. There should be a closer coupling between industry and universities. There are significant and unnecessary delays for the use in industry of what has been developed in the universities.

5. A large gap exists between commercially available vision equipment and the capabilities demonstrated in the research community. This gap needs to be, and can be, filled in the near future. There is a definite need to develop that equipment.

6. Knowledge of orientation and position has economic value. This value can be measured, for example, by the cost of the most economic means of regaining the lost knowledge and perhaps even physically regaining the position and orientation.

7. There are many applications where vision is necessary.

8. Vision systems should aspire to many of the same

attributes as good arms, such as reliability, low cost, wide applicability, speed, and programmability.

9. The importance of considering the entirety of a vision system, including lighting, hardware, and software, a concept presented by the Vision I group, was endorsed.

10. Vision hardware might more frequently be used in robot installations if robot manufacturers approached vision hardware companies with a general list of vision needs or if end users specified their needs to the extent required for total system development.

B. Group Report

Group discussion included the schedule for the introduction of robots which could handle the bin-of-parts problem. It was agreed that complex problems, such as bin picking, could be made simpler technically by introducing various mechanisms, but this can lead to unacceptable costs. In general, bin-picking robots might be expected to be introduced first in slower cycle time applications. With time, the number of parts which can be presented from bins by robots will increase and the cycle time will decrease. For low cycle times, multiple arms or hands which can reorient parts will probably be necessary.

Group discussion also endorsed continued research on the uses of a camera in the gripper and stereo vision. This work was categorized as a medium-term industrial need. It was decided that to list all the applications where vision is necessary would have taken too long. It is probably possible to list generic categories of vision applications, but the group didn't work on this.

Joint discussion after the Vision II report first centered on the need for a listing of who is doing research on robots, what are they doing, and what equipment is available. It was agreed that such a compendium was needed. Some existing sources for this information are the Smithsonian Institution's Science Information Exchange and the Illinois Institute of Technology Research Institute's report on CAD/CAM and Socio-Technical Research. Forthcoming sources of this kind of information are the new magazines "Robotics Today" and "Robotics Age".

There was also a discussion of the major responsibility for the introduction of vision in robot applications in industry. Generally it was agreed that users would play the most

important role. Robot suppliers can be expected to contribute, mostly emphasizing simple vision with widespread applications. Vision systems can be expected to come from other companies also. It was felt that having responsibility for a system consisting of a robot and a vision module may pose problems since robot manufacturers weren't likely to move into vision in a vigorous way and companies capable of building vision hardware probably wouldn't want responsibility for an expensive arm. Another problem might be that users would like to specify vision systems in terms of the application objectives instead of the computational goals. It was mentioned that vision was application specific. On the other hand, it also seemed likely that some components of a vision system were generally useful and thus we might expect the use of reasonably general systems which can be tailored to different applications.

III. DELPHI FORECAST

INTRODUCTION

A list of 10 questions relating to sensors, control system capabilities, and market predictions was distributed to the participants before the workshop.

The Delphi was conducted in three rounds. For the first round, the questionnaires were mailed to the participants and filled out before the workshop. These were discussed the first evening, and a second set of questionnaires was prepared the next morning. This second round was discussed the afternoon of the second day. A third set of questionnaires was then prepared and handed in at the end of the workshop. The results of this third round are presented here.

For most answers, the results are in the form of three numbers. The first number is the arithmetic mean of all the responses. The next two numbers are the cutoff values for the upper and lower quartiles. For example, the responses to a question involving the prediction of the year for an event were summarized as follows:

1985
1984-1987

Here, the mean of all responses is the year 1985. The middle 50 per cent of the responses fell between the years 1984-1987, while 25 per cent of the responses were less than 1984 and 25 per cent were greater than 1987.

This questionnaire covered a large range of application areas. The respondents were advised to fill in only that part of the questionnaire that concerned the area(s) with which they were most familiar.

SENSORS

Question 1a)

This question was concerned with the importance of different types of sensors in terms of their immediate economic benefit for the user. This takes into consideration the cost for the sensor in relation to the relative increase in capability it might give a particular application. For example, consider spot welding of automobile bodies. The addition of simple vision or proximity sensors could allow the robot to accurately place the welds on cars carried by existing transfer lines. This would eliminate the need of the additional expensive indexing and positioning equipment that presently has to be installed for robots to perform this

task. Thus, these sensory capabilities received a high ranking for spot welding because of the large economic benefits they would provide if available. In some applications, such as press loading/unloading, none of the sensory capabilities received very high rankings. This reflected the consensus that there is not much need for sensors in these applications, or at least, that there is presently not much immediate economic benefit to be derived from installing sensors in these applications.

Comments on 1a)

In completing the questionnaires for the third time, the participants were asked to provide written comments if their responses differed significantly from the average values obtained in the second round.

There was significant disagreement on the value of sensors for spot welding and press loading/unloading. Some of the opinions expressed were:

"The use of sensors for spot welding and press loading/unloading is largely unnecessary. Sensors will not be applied if they slow down program execution. Cycle time is critical in these operations."

"Spot welding is a well-accepted robot application even without the use of sensors. However, a proximity or simple vision sensor which would ensure the proper placement of the weld flange would be very beneficial."

"If one were building a spot welding line from scratch, the economic tradeoff between sensors and fixturing would be much more apparent than shown above."

"Simple vision enables the assembly being welded to be much more coarsely positioned. This reduces transfer machine costs and increasing the probability of a good weld. The need for hand rework of defects is reduced."

"Simple inexpensive touch and proximity sensors are available today, and it would appear that there should be a much higher immediate economic benefit when used in assembly than the average shows."

"An appropiate sensor for arc welding may be none of these listed. The economic benefit that could be obtained with a sensor which could track the seam and change process parameters with the gap exceeds the economic benefits which could be acheived with sensors in any application area."

SENSORS

1a) Using the matrix below, rank the listed sensors in order of importance (1 through 6) for immediate economic benefit to the user. Fill in only the rows that correspond to the application area(s) you are familiar with. (You may give two or more sensors equal rank.)

	Touch*	Simple Force	Complex Force	Proximity	Simple Vision	Complex Vision
Spot Welding	3.7 (2-6)	4.1 (3-5)	4.9 (4-6)	2.1 (1-3)	2.1 (1-2)	5.4 (5-6)
Arc Welding	4.4 (4-6)	4.7 (4-6)	5.2 (5-6)	2.5 (2-3)	1.2 (1-2)	3.4 (2-5)
Drilling, Routing Grinding, etc.	4.1 (3-5)	2.4 (1-3)	2.9 (2-3)	4.4 (3-6)	1.8 (1-2)	3.9 (2-6)
Small Part Assembly	3.8 (3-5)	2.6 (2-4)	3.4 (3-4)	3.9 (3-5)	1.7 (1-2)	2.1 (1-3)
Machine Tool Loading/Unloading	2.8 (2-4)	3.4 (3-4)	4.6 (4-6)	3.1 (2-3)	2.3 (1-3)	3.6 (2-6)
Press Loading/Unloading	2.5 (2-3)	3.1 (2-4)	4.8 (4-5)	3.0 (2-3)	2.7 (1-4)	4.1 (3-6)

* Touch - presence or absence of parts or displacement along one axis
Simple force - measure force along a single axis
Complex force - measure force along two or more axes
Proximity - non-contact detection of part
Simple vision - detect edges, holes, corners, etc.
Complex vision - recognize shapes

Question 1b)

This question attempted to quantify to some degree the cost that a potential user felt he or she could justify for a particular sensor capability.

SENSORS

1b) For the sensors from question 1a, enter the cost that can be justified for the increased performance the sensor gives the robot system.

Sensor Capability from 1a	Cost Justified per Robot (dollars)
Touch	$1700 (300-2500)
Simple Force	$3200 (2500-4000)
Complex Force	$6200 (4500-6000)
Proximity	$2300 (1000-3000)
Simple Vision	$10,800 (10,000-15,000)
Complex Vision	$23,000 (20,000-30,000)

Question 1c)

This question addressed a different time frame than 1a). In question 1a), the participants were to prioritize sensory capabilities in terms of immediate short-term economic benefit in their applications. Here, they are being asked to set a priority for research on sensors. That is, on what sensor systems should the research institutes expend their money and resources to provide the highest long-term benefit? The results are expressed in the same form as in question 1a).

1c) Using the matrix below, rank the listed sensors in order of priority (1 through 6) for expenditure of research and development money. Again, only fill in the row(s) that corresponds to the area(s) you are familiar with. You may give two or more sensors the same rank.

	Touch*	Simple Force	Complex Force	Proximity	Simple Vision	Complex Vision
Spot Welding	4.0 (3-4)	3.6 (2-4)	5.0 (4-6)	2.5 (2-3)	1.7 (1-2)	5.0 (5-6)
Arc Welding	5.1 (4-6)	4.8 (4-6)	4.9 (3-6)	3.0 (2-4)	1.1 (1-1)	3.3 (2-5)
Drilling, Routing Grinding, etc.	4.6 (4-5)	2.2 (1-3)	2.9 (2-3)	4.6 (4-5)	1.8 (1-2)	3.5 (2-4)
Small Part Assembly	4.5 (4-5)	2.9 (2-4)	2.9 (2-3)	3.8 (3-5)	1.4 (1-2)	1.8 (1-2)
Machine Tool Loading/Unloading	3.9 (2-5)	3.7 (3-5)	4.4 (3-6)	3.2 (2-4)	1.7 (1-3)	2.9 (2-4)
Press Loading/Unloading	3.1 (2-4)	3.5 (2-4)	4.6 (4-5)	3.3 (3-4)	2.3 (1-3)	3.6 (2-6)

The following are the responses for questions 2 through 10.

SENSORS

2) For each of the sensors below, predict the year when robots will be commercially available with that capability and predict the percentage of robots shipped in 1985 that will have that capability.

	Year Commercially Available at the Price in 1b)	% of Robots Shipped in 1985 with That Capability
Touch	1980 (1979-1980)	38% (10%-50%)
Simple Force	1980 (1980-1981)	19% (10%-20%)
Complex Force	1983 (1982-1984)	11% (3%-10%)
Proximity	1980 (1979-1980)	22% (10%-20%)
Simple Vision	1981 (1980-1982)	18% (10%-20%)
Complex Vision	1984 (1982-1985)	10% (1%-10%)

3) Enter the percentage of work in the application area(s) you are familiar with that is characterized by the degree of part misalignment described in each column of the matrix below. Within an application area (a row in the matrix), the percentages should sum to 100%.

	Ultra Precise	Precise	Crude	Surface	Random
Spot Welding	10 (0-15)	59 (50-75)	27 (10-30)	4 (0-5)	0 (0-0)
Arc Welding	12 (0-15)	52 (35-65)	31 (20-35)	5 (0-10)	0 (0-0)
Drilling, Routing Grinding, etc.	28 (0-30)	46 (30-50)	22 (10-30)	4 (0-5)	0 (0-0)
Small Part Assembly	25 (10-35)	29 (25-40)	13 (5-20)	18 (10-20)	15 (5-20)
Machine Tool Loading/Unloading	11 (0-20)	32 (20-45)	25 (14-40)	12 (5-16)	20 (5-20)
Press Loading/Unloading	14 (0-20)	25 (15-35)	20 (10-20)	18 (10-20)	23 (5-30)

* Ultra Precise - locate part where position known to < .050"
Precise - locate part where position known within .050", 1 degree
Crude - locate parts were position is known within 1", 20 degrees
Surface - locate parts on a known surface but within a random orientation and position (e.g. part randomly oriented on a conveyor)
Random - locate parts with large displacements in all three positional coordinates and all three rotational coordinates (e.g. bin picking)

4) What percentage of the tasks in the application area(s) you are familiar with require the robot to be able to track a moving line? In what percentage of tasks would it be useful for the robot itself to be mounted on a moving platform?

	Percentage of Applications Requiring Line Following	Percentage of Applications In Which Robot Mobility Would be Useful
Spot Welding	47% (40%-50%)	20% (10%-20%)
Arc Welding	15% (5%-20%)	23% (15%-25%)
Drilling, Routing Grinding, etc.	5% (0%-10%)	25% (15%-30%)
Small Part Assembly	17% (10%-35%)	12% (5%-15%)
Machine Tool Loading/Unloading	11% (5%-15%)	28% (20%-30%)
Press Loading/Unloading	5% (2%-6%)	20% (10%-25%)

CONTROL

5) Estimate for each of the years given below the percentage of robots shipped in the U.S. market that will have the control capabilities listed. Each column should sum to 100%.

	1980	1985	1990
Point-to-Point Adjustable Stops	28 (19-38)	18 (13-18)	12 (8-16)
Servo Point-to-Point	44 (38-52)	33 (27-35)	27 (12-29)
Continuous Path	12 (10-14)	22 (13-27)	21 (16-29)
Coordinate Transformation (straight line, joystick, line following)	12 (10-19)	21 (13-27)	27 (16-29)
Trajectory Optimization	2 (0-5)	6 (2-9)	13 (8-12)

CONTROL

6) For each of the years given below estimate the percentage of robots shipped in the U.S. market that will utilize the teach/program method listed. Each column should sum to 100%.

	1980	1985	1990
Sequence, Adjustable Stops	26 (20-30)	19 (15-20)	12 (8-17)
Teach-Playback (rate control box)	41 (35-50)	25 (20-30)	16 (8-21)
Teach-Playback in External Coordinates (joystick, xyz, etc.)	20 (10-25)	22 (19-25)	17 (8-21)
Teach-Playback with Editing	11 (5-15)	20 (15-30)	25 (17-29)
Off-Line Programming/ Higher Level Languages	2 (0-5)	11 (5-15)	22 (13-25)
Automatic Programming Computer Generates Robot Program	0 (0-0)	3 (0-5)	8 (3-13)

7) For the years listed below, estimate the percentage of robots that will be incorporated into integrated computer-aided manufacturing systems.

	1980	1985	1990
Percentage of Robots in Integrated Systems	2.1 (1-5)	9.9 (5-10)	25 (15-30)

8) For each of the performance characteristics described in the columns below, enter a number from 1 to 5* to indicate its importance to the application area(s) you are familiar with. You may give more than one characteristic the same rank.

	Fast Short Moves	High Slewing Speeds	High Positional Accuracy	Sensor Directed Control	Fast Programming	Off-Line Programming
Spot Welding	1.0 (1-1)	2.0 (2-2)	2.3 (1-3)	2.9 (2-3)	3.0 (3-3)	3.7 (3-4)
Arc Welding	3.9 (3-5)	3.2 (3-4)	1.4 (1-2)	1.0 (1-1)	2.5 (2-3)	3.7 (3-4)
Drilling, Routing Grinding, etc.	2.7 (1-4)	3.4 (2-5)	1.0 (1-1)	2.6 (1-3)	2.0 (2-2)	2.0 (2-2)
Small Part Assembly	1.7 (1-2)	2.0 (2-2)	1.0 (1-1)	1.6 (1-2)	2.7 (2-3)	3.3 (2-4)
Machine Tool Loading/Unloading	2.2 (2-3)	1.5 (1-2)	2.6 (2-3)	2.8 (2-3)	3.0 (3-3)	3.9 (3-4)
Press Loading/Unloading	2.6 (2-3)	1.4 (1-2)	2.6 (1-3)	2.9 (2-4)	3.0 (3-3)	3.9 (3-4)

* 1 - critical to the application
2 - highly advantageous for more effective and efficient use of robot
3 - offers some advantages but not absolutely necessary
4 - may need this capability sometime
5 - never need this capability

MARKET

9) Estimate the number of robots shipped by U.S. manufacturers and the dollar value of these shipments for each of the years listed.

	1980	1985	1990
Number of Robot Units Shipped	1170 (800-1500)	4800 (3500-6000)	17100 (10,000-20,000)
Dollar Value of Shipments ($M)	60 (50-75)	225 (175-270)	780 (450-1000)

This corresponds to approximately a 30% per year growth rate both in dollar volume and in units shipped.

RESEARCH PROPERTIES

10) Give the percentage of research funds/effort which you feel should be targeted to each of the areas below.

Off-Line Programming	12	(5-15)
Control Systems	11	(9-15)
Mechanical Systems	7	(5-10)
End Effectors	10	(5-10)
Touch, Force, Torque, Sensing	11	(9-14)
Binary Vision	14	(10-17)
Gray Scale Vision	12	(5-15)
Integration Into CAM Systems	8	(5-10)
Safety	4	(2-5)
Mobility/Line Tracking	4	(0-5)
Simulation and Modeling	6	(3-10)
Others	1	(0-1)
	100%	

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10. SUPPLEMENTARY NOTES

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The NBS/RIA Robotics Research Workshop had two objectives: 1) To provide a forum for structured discussions between researchers in robotics and manufacturers and users of robot systems and 2) To develop a consensus forecast of future developments in sensors and control systems for industrial robots.

The 3-day workshop brought together 31 researchers, manufacturers, and users of industrial robots in order to determine the needs and priorities for future research in sensors and control techniques for industrial robots. There were no formal papers; instead, small group discussions and presentations and the preparation of a Delphi Forecast were used to address research needs and priorities.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Delphi Forecast; robot control; robot vision; robotic assembly; robotic standards; robotics research

13. AVAILABILITY

[x] Unlimited

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